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# Nucleosynthesis Above the Iron Group in Massive Stars

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The production of nuclei up to and including the light *s*-process component at A $\approx$ 60-90 is calculated for all stages of stable and explosive nuclear burning in stars of 15 and 25 $M_\odot$. An extended nuclear reaction network of 480 isotopes is employed along with approximately two dozen recent revisions to key nuclear reaction rates. As noted previously, the new rates suggest a greatly diminished production of $^{17}O$ and $^{18}O$ in massive stars. $^{22}Ne$ is also moderately enhanced. We find that a combination of pre-explosive *s*-process, $\gamma$-process, and (mild) *r*-processes in massive stars give a consistently solar production of almost all isotopes from mass 64 through 90. However, even after the late stages of evolution are complete and the explosion is over, this same group of elements is overproduced compared to what is needed for the sun, especially in the 25 $M_\odot$ model.

## 1. INTRODUCTION

Six years ago a systematic survey of nucleosynthesis in massive stars was carried out by Woosley & Weaver (1995; henceforth WW95). During the intervening period a number of important reaction rates have been measured or recomputed, especially for nuclei lighter than silicon. Angulo et al. (1999) (also known as the "NACRE collaboration"); Rauscher & Thielemann (2000); and Langanke & Martinez-Pinedo (2000) have published major revisions to reaction rates below silicon, Hauser-Feshbach rates above silicon, and weak interaction rates, respectively.

Here we examine the evolution of two stars - similar to S15A, and S25A of WW95. The reaction rate set and stellar physics employed will be the same as WW95 with the exception of about two dozen reaction rates below $^{28}Si$ that have been recently revised and the nuclear reaction network contains 480 isotopes (compared with 198 used by WW95). Thus it is sufficiently large to follow the weak component of the *s*-process ($60 < A < 90$) through all stages of nuclear burning and explosion in a self-consistent stellar model. We are also able to follow the explosive modification of these trace isotopes as the star blows up and track the production of light *r*- and *p*-process isotopes. Details of the rate revisions will be deferred to Hoffman, Woosley, & Weaver (2000).

In subsequent papers (Rauscher et al. 2000), we will include new stellar physics (neutrino loss rates, opacities, mass loss), a revised rate for $^{12}C(\alpha,\gamma)^{16}O$, and the other new

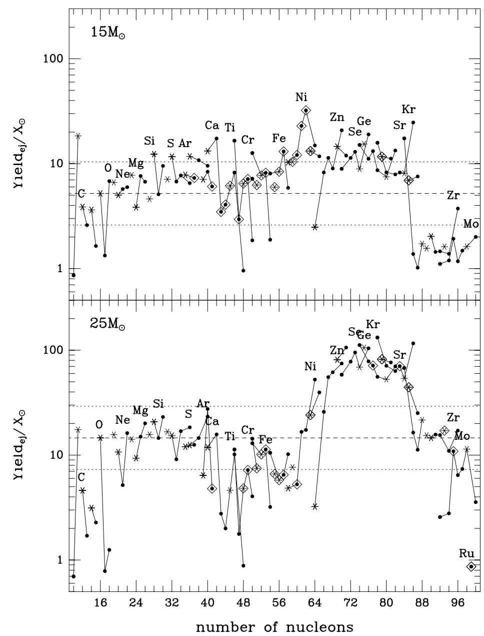


Figure 1. Production factors in the ejecta of a 15 and 25 $M_\odot$ star relative to solar abundance.

nuclear reaction rate sets listed above. The nuclear reaction network in this next generation of models will include up to 2500 isotopes (complete through polonium) and will be "adaptive" in the sense that nuclei will be added and subtracted to follow strong flows. The first set of these (Rauscher et al. 2000) will be only for 15, 20, and 25 $M_\odot$ solar metallicity stars, but will serve as a test bed for the physics to be included in a full survey, sometime next year, of approximately 300 stars of varying mass and metallicity.

## 2. Results

Production factors for the isotopes from boron through molybdenum are given for the two stars studied in Fig. 1. Species surrounded by a diamond are (chiefly) made as radioactive progenitors, those marked by a "star" are the most abundant species for a given element. A "success band" (bounded above and below by a factor of two) has been centered on $^{16}$O. Especially for the 25 $M_\odot$ star, and, to a lesser extent the 15 $M_\odot$ star, the large production between A = 64 and 90 is due to a combination of *r*-, *s*- and *p*-processes prior to the explosion. That a weak component of the *s*-process occurs in massive stars with neutrons provided by $^{22}$Ne($\alpha$,n)$^{25}$Mg near the end of core helium burning has been known for a long time. It is also known (e.g., WW95, Rayet et al. 1995, and references therein) that photo-disintegration reactions acting during the explosion on both these *new* *s*-process nuclei (up to A = 90) and old primordial *s*-process nuclei can produce *p*-process nuclei. An interesting new result (Hoffman et al. 2000) is that a lot of this *p*-process activity goes on *prior* to the explosion in the oxygen burning shell. A weak *r*-process (or more properly a "strong *s*-process") occurs in the convective carbon and neon shells of the pre-supernova star with neutrons still provided by $^{22}$Ne($\alpha$,n)$^{25}$Mg and $^{26}$Mg($\alpha$,n)$^{29}$Si. This produces a handful of nuclei bypassed by the classical *s*-process like $^{70}$Zn, $^{76}$Ge, $^{82}$Se, $^{86}$Kr, $^{87}$Rb, and, to a lesser extent, $^{96}$Zr, and $^{100}$Mo.

The production of all these "trans-iron group" nuclei is both good and bad news. It is good news that one can co-produce, as a group, large quantities of so many isotopes in near solar proportions. The bad news is that this may be too much of a good thing (compared to $^{16}$O, say, in the 25 $M_\odot$ model). The 15 $M_\odot$ model has a more nearly solar proportion of these nuclei. Since the *s*-process is secondary, it is actually important to over-produce it slightly in stars of solar metallicity. The new rates lead to slight changes in the *s*-process, particularly an enhancement of nuclei heavier than the iron group in the 25 $M_\odot$ star (where they were already overproduced - see above). However the changes are not large (typically less than 40%). Whether there is real cause for concern will become apparent only after a careful study of many stars of varying mass and metallicity is carried out, with subsequent integration of the resulting stellar yields in a model for Galactic chemical evolution. This may be indicative of a more general problem to come with the absolute yields of trans-iron group species. Likely culprits might include poorly measured (or modeled) nuclear reaction rates, uncertainties in the convective model, and mass loss. In fact, preliminary calculations by Rauscher et al. (2000) which include mass loss suggest that the *s*-process production in a 25 $M_\odot$ star is reduced owing to its smaller helium core size.

Another aspect of the revised nuclear reaction rates is a substantial reduction in the production of $^{17}$O and $^{18}$O. In fact $^{17}$O production is so reduced that it can no longer be considered a product of massive stellar evolution and its synthesis must be relegated to classical novae (e.g., Jordi & Hernanz 1998). The culprits here are the new larger rates for $^{17}$O(p,$\alpha$)$^{14}$N and $^{17}$O(p,$\gamma$)$^{18}$F that greatly reduce $^{17}$O production in the hydrogen envelope. The neutron-rich isotope $^{18}$O, made in helium burning by $^{14}$N($\alpha, \gamma$)$^{18}$F(e$^+\nu$)$^{18}$O, is destroyed by a more efficient rate for $^{18}$O($\alpha, \gamma$)$^{22}$Ne leading in some stars (e.g., 15 $M_\odot$) to an increased yield of $^{22}$Ne.

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## REFERENCES

1. S.E. Woosley and T.A. Weaver, Ap. J. Suppl. 101 (1995) 181.
2. C. Angulo, et al., NP A656 (1999) 3.
3. T. Rauscher and F.-K. Thielemann, ADNDT 75 (2000) 1.
4. K. Langanke and G. Martínez-Pinedo, NP A673 (2000) 481.
5. R.D. Hoffman, S.E. Woosley, and T.A. Weaver, Ap. J. (2000) submitted.
6. T. Rauscher, R.D. Hoffman, A. Heger, S.E. Woosley, Ap. J. (2000) in prep.
7. M. Rayet, M. Arnould, M. Hashimoto, N. Prantzos, K. Nomoto, A&A 298 (1995) 517.
8. J. Jordi, & M. Hernanz, Ap. J. 494 (1988) 680.